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Water storage and evaporation as constituents of rainfall interception

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Abstract

Intercepted rainfall may be evaporated during or after the rain event. Intercepted rain is generally determined as the difference between rainfall measurements outside and inside the forest. Such measurements are often used to discriminate between water storage and evaporation during rain as well. Two well-accepted methods underestimate water storage by a factor two as compared to direct observations. The underestimation of storage is compensated by an overestimation of evaporation during rain by a factor of three. The direct observations of water storage and evaporation appear to agree with previous direct observations. Thus, it is concluded that these observations are representative. Also, our results based on methods using only rainfall measurements inside and outside the forest appear to agree with previous results. This would result in the conclusion that the common methods systematically underestimate water storage and overestimate evaporation during rain. Indeed, the systematic errors can be explained by the neglect of drainage before saturation. Water storage is better simulated assuming an exponential saturation of a larger storage capacity. A smaller evaporation can be simulated using an appropriate resistance to vapour transport. The observations in dense coniferous forest showed water storage to be the dominant process in rainfall interception, but this conclusion should not be generalized to other forests and climates. Direct observations of water storage and evaporation are recommended to build a realistic set of parameters for rainfall interception studies of the main vegetation types.

Keywords: Rainfall interception; Water storage; Evaporation

1. Introduction

Interception is that part of the rain that falls on the vegetation and evaporates without reaching the ground. Interception is thought to be considerable, especially for aerodynamically rough vegetation like forests, due to its high aerodynamic conductance, which may result in a high evaporation rate. Interception amounts to 10–50% of the precipitation on forest and accounts for an even higher percentage of the total water use of forests. The fraction of intercepted and evaporated rain is not only rather large, but also very variable in time. In particular, a higher fraction is intercepted from small rain events. This is easily understood, as part of the rain is stored in the canopy. As long as the canopy is unsaturated, a high fraction of rain can be intercepted. When the canopy is saturated, most rain that falls on the vegetation will drain to the ground and interception can only increase by evaporation during rain.

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Stored water will evaporate when the rain has stopped. So, the concept of storage implies a distinction of interception (I) into evaporation during rain (Et) and evaporation after rain, which equals water storage at the end of the rain event (C_e):

$$I = C_e + Et. \tag{1}$$

The subscript 'e' denotes the value at the end of an event. Interception and storage are given in mm, and the evaporation rate E in mm h^{-1} averaged over the rain event of duration t in h. Discrimination between water storage and evaporation during rain is primarily significant for a realistic description of rainfall interception. Moreover, evaporation of stored water after rain hinders transpiration. Restricted transpiration is relevant to models of forest water use and growth. Also, evaporation during rain results in a quick return of water into the atmosphere, resulting in a positive feedback on rainfall (Lean and Rowntree, 1993).

The problem with Eq. (1) is the difficulty in determining C_e and Et. Measurements of evaporation strongly deteriorate when the relevant sensors are wetted by rain, and instruments to measure water storage have not (yet) become common. Due to the difficulty of direct observations, the distinction between C_e and Et is generally made indirectly. It can be derived from rainfall observations inside and outside the canopy using some assumption on the process of interception. The methods used to calculate C_e and Et from rainfall observations only are denoted in this study as 'indirect' methods.

The aim of this study is to validate some indirect methods. The validation is based on direct observations of water storage and evaporation. Water storage was determined from the microwave transmissivity of the forest canopy (Bouten et al., 1991) and evaporation was determined from eddy correlation and flux gradient measurements (Bosveld, 1997).

At an early stage of the study, it became obvious that the existing indirect methods did not agree with the direct observations. According to the error analysis, the indirect methods are the most suspect. So, a new indirect method to divide I into C_e and Et has been derived, based on the parameters that are most important in controlling interception.

2. Theory

2.1. The interception process

The description of the interception process is based on Rutter et al. (1971). A fraction p of the precipitation P (mm) reaches the forest floor directly; the remaining part $(1 - p)$ touches the canopy and may be temporarily stored (C; in mm), evaporated to the atmosphere (E; in mm h^{-1}) or drained to the forest floor (D; in mm h^{-1}). Drainage may occur directly by canopy drip or by stemflow. Changes in stored water are given by:

$$\delta C/\delta t = (1 - p)R - E - D, \tag{2}$$

where R is rain rate ($R = \delta P/\delta t$ in mm h^{-1}). Integrating Eq. (2) over a rain event and using $T = Dt + pP$ results in:

$$C_e = (1 - p)P - Et - T + pP,$$

so

$$I = C_e + Et = P - T, \tag{3}$$

where I is interception (mm), and T is the sum of throughfall and stemflow (mm), which equals rainfall underneath or inside the canopy. Note that, in some studies, P is denoted as 'gross precipitation' and T as 'net precipitation'. Two assumptions have been made in Eq. (3): (1) rain events are separated by dry periods long enough to dry the canopy completely, and (2) canopy drainage is negligible after the rain has stopped.

2.2. Estimation of water storage capacity

Water storage capacity S (mm) is defined as the maximum possible water storage after quick drainage has stopped. Three methods will be presented to calculate S using a scatter plot of measured I versus P. Note that, in some studies, the estimation has been based on a scatter plot of T versus P. In this study, we prefer I $(= P - T)$ as a basis, as it yields the least stochastical errors when rainfall outside the canopy is measured without observational scatter and rainfall inside the canopy is observed with scatter. It will appear that the various methods of estimating S will result in slight variations in the exact definition.

Therefore, the notation of S is adapted to the method. The methods are described below.

2.2.1. The mean method

The most simple and rather elegant way to simulate water storage is to assume $D = 0$ for $C < S$. Based on this 'waterbox' concept, it is reasonable to divide the scatter plot of I versus P into two parts: a wetting part when $P < P_s$ (P_s is the precipitation needed to reach saturation, saturation meaning $C \geq S$ in the waterbox concept) and a saturated part when $P \geq P_s$. Interception during wetting is then given by:

$$P < P_s: \ D = 0, \ \text{so}: \ I = P(1 - p). \tag{4}$$

Supplementary interception during saturation is given by:

$$P \geq P_s: \ \delta I/\delta P = \delta C/\delta P + \delta(Et)/\delta P. \tag{5}$$

Although C may temporarily exceed S during rain, this excess will quickly drain. Quickly after the rain has stopped, we may assume $C_e = S$, or $\delta C_e/\delta P = 0$, for $P \geq P_s$. By further assuming a constant ratio between E and R during rain (Gash, 1979) and using Eq. (4), Eq. (5) is integrated to:

$$I = (1 - p - E/R)P_s + (E/R)P. \tag{6}$$

Interception and precipitation can then be plotted for a large number of rain events. A linear regression of the type $I = \alpha P + \beta$ for $P \geq P_s$ results in estimates of $\alpha = E/R$, the ratio of evaporation to rainfall, and $\beta = (1 - p - E/R)P_s = S_{mean}$, the mean water storage capacity (mm). This method is denoted the 'mean method' in this study, as it is based on a least square fitting of data. Eq. (6) has been in common use since Horton (1919) used it to estimate S_{mean}. It has also been used to estimate the evaporation rate (see Table 2), although this was not intended, by Gash (1979). A refinement has been introduced to compensate for a lower evaporation rate (E^*) during wetting. By assuming (Rutter et al., 1971):

$$E^* = (C/S)E \ \text{for} \ P < P_s, \tag{7}$$

Eq. (2) results in:

$$\begin{aligned} &\delta C/\delta t = (1 - p)R - (C/S)E \\ &C = (1 - p)RS/E\{1 - \exp(-Et_s/S)\} \\ &t_s = -(S/E)\ln\{1 - (E/R)/(1 - p)\} \\ &P_s = Rt_s = -(RS/E)\ln\{1 - (E/R)/(1 - p)\}, \end{aligned} \tag{8}$$

where t_s is time needed to reach saturation. Then, linear regression of the form $I = \alpha P + \beta$ results in (Gash, 1979):

$$\begin{aligned} &\beta = -S(1 - p - \alpha)/\alpha \ln\{1 - \alpha/(1 - p)\} \\ &\text{or}: \ S = -\alpha\beta/[(1 - p - \alpha)\ln\{1 - \alpha/(1 - p)\}]. \end{aligned} \tag{9}$$

The following example may show the significance of this refinement. Using $\alpha = p = 0.1$ and $\beta = 1$ mm results in $S_{mean} = 1$ mm (Eq. 6) and $S = 1.06$ mm (Eq. 9). As the difference is small with regard to measurement accuracy, we will use the most simple expression (Eq. 6).

2.2.2. The minimum method

Leyton et al. (1967) argue that most of the scatter in the I versus P plot is caused by a variable number of wetting cycles during intermittant rain, or—more generally—by variable evaporation. By fitting a line through data with minimum I for $P \geq P_s$, the effect of variable evaporation is suppressed. Moreover, the refinement of Eq. (9) becomes even smaller, so the simplification $S_{min} = \beta$ is more accurate. This method is denoted as the 'minimum method' because the fitting is restricted to data with minimum interception. The method excludes data points with $I < 0$, which are thought to be caused by condensation (dew) or measurements below dripping points. Disadvantages of the method are the subjective choice of the data that are used, and the waterbox assumption.

2.2.3. The maximum method

The mean and minimum water storage capacities are based on the waterbox concept, with $D = 0$ for $C < S$ and an abrupt change to $D = (1 - p)R - E$ for $C = S$. Gradual saturation of the canopy, with D progressively increasing with C, is encountered because:

1. Rain drops may splash on an already wetted part of the canopy (Calder, 1986).

2. Bark and bottom sides of leaves saturate slowly (Herwitz, 1985).
3. Upper leaves shelter lower leaves.

Gradual saturation can be modelled using an exponential equation (Aston, 1979):

$$C = S_{max}\{1 - \exp(-\gamma P)\}, \quad (10)$$

where γ is taken as a fitting parameter. Theoretically, γ can be calculated using $\gamma = (1 - p)/S_{max}$ and p can be estimated from the visible fraction of gaps in the canopy. Using Eq. (10), total interception can be calculated using (Merriam, 1960):

$$I = S_{max}\{1 - \exp(-\gamma P)\} + (E/R)P. \quad (11)$$

The disadvantage of this method is that the parameters γ, (E/R) and S_{max} cannot be estimated independently of the I versus P scatter plot with sufficient accuracy. A simplification of Eq. (11) is used by Calder (1990):

$$I = X\{1 - \exp(-\gamma P)\}, \quad (12)$$

where X is an empirical fitting parameter, describing the interception for large rain events. Contrary to Calder (1990), we will use Eq. (12) on an event basis and set $X = S_{max}$. Using this definition, S_{max} includes evaporation and should result in an overestimation of actual water storage capacity. Based on Eq. (12), water storage can be calculated at any time during the rain event using:

$$C = S_{max}\{1 - \exp(-\gamma P)\} - Et. \quad (13)$$

As compared to Eq. (11), the parameters of Eq. (12) can be determined more accurately. The method resembles the exponential wetting function (Eq. 10), but Eq. (13) includes a release of stored water by evaporation. A small decrease of water storage with evaporation is reasonable, as the storage is only slowly refilled after evaporation. For higher evaporation values, however, the physical meaning of S_{max} is reduced. The simplification $X = S_{max}$ was included to keep the input data requirements in line with the minimum method.

2.2.4. Evaluation of methodological differences

The mean and minimum methods are based on the waterbox concept and lose reality when drainage is large compared to storage for $C < S$. The maximum method loses reality when evaporation is large compared to storage. The difference in the main assumption of the methods was introduced explicitly to get a better understanding of the relevant processes in rainfall interception.

The ‘mean’ method results in estimates of both water storage capacity and evaporation during rain. The ‘minimum’ method only results in an estimate of water storage capacity; interception should be calculated using an estimate of evaporation. The ‘maximum’ method results only in an estimate of interception; water storage should be calculated using an estimate of evaporation. So, the ‘minimum’ and ‘maximum’ methods require the same input data, whereas the ‘mean’ method requires only measurements of rainfall outside and inside the canopy. A further difference is that the ‘minimum’ and ‘mean’ methods result in a constant water storage at the end of all rain events with $P \geq P_s$ and the ‘maximum’ method results in variations according to Eq. (13).

3. Measurements

3.1. Site

The measurements were carried out in the Speulderbos in the centre of the Netherlands as part of the ACIFORN project on the effect of atmospheric deposition on forest vitality. A patch of 2.5-ha, 27-year-old Douglas fir is surrounded by patches of Scotch pine, oak, beech, larch and Douglar fir. Tree density is about 800 ha^{-1}, tree height 18 m, and leaf area index varies between 9 and 13 throughout the year.

3.2. Water storage and rainfall

Water storage was measured using microwave transmission (Bouten et al., 1991) with a vertically moving system. The attenuation of a 10-GHz signal was measured over a horizontal distance of 15 m with a vertical resolution of 1 m from the forest floor to the tree tops, and a time resolution of 5 min. Six measurements have been averaged to obtain 30-min data. The measurements were calibrated on the water budget in periods of low evaporation (nights with low windspeed), with an estimate of evaporation to diminish possible errors related to evaporation (Bouten and Bosveld, 1991).

Rainfall outside the canopy was measured just above the forest and in a clearing about 0.8 km away. The measurements did not show any systematic deviations. Therefore, the nearest measurements (above the forest) were used. Rainfall above the canopy was measured by two 480-cm^2 rainfall funnels with 0.02 mm resolution. Rainfall inside the canopy was measured by 11 automatic funnels and calibrated on 36 manually operated funnels. Stemflow has been neglected. Although Robins (1974) observed significant stemflow in an old Douglas fir forest, visual inspection did not show any sign of stemflow in the forest where the experiment was conducted, probably due to the high leaf area index.

3.3. Evaporation

Evaporation is estimated in two ways. Firstly, from the profile method on the basis of psychrometer profile measurements (Duyzer et al., 1992) at 24 and 36 m height, and secondly on the basis of an energy balance method:

$$\lambda E = Q_n - G - H, \tag{14}$$

where λ is the latent heat of vaporization, Q_n is the net radiation measured by a Funk-type net radiometer, G is the heat storage term, modelled with a force restore model driven by the measured forest interior air temperature, and H is the sensible heat flux measured with a sonic anemometer thermometer system (Kaijo Denki DAT 300) at 30 m height. When both methods yielded realistic results, the average of both methods was used.

The measured latent heat flux is the sum of transpiration and evaporation. In order to obtain the evaporation of intercepted rain, the measurements have been corrected for transpiration. This estimate was derived from a big leaf model tuned to $L\gamma$–α eddy correlation flux measurements on dry days, which has been extended to wet periods on the basis of sap flow measurements.

3.4. Data selection

Rainfall data inside and outside the canopy (net and gross preciptation) were used from June to December 1989. The data were analysed on an ‘event’ basis. A rain event has been defined as a period of rain, preceded by a dry period of at least 2 h. Optimally, an event should start with a dry canopy and consist of continuous rain. By using the observations of water storage, it was distinctly possible to select only events which started with a dry canopy, but a selection on dry periods was preferred, as it is in better agreement with studies where only rainfall data were available. By taking the dry period too short, events are included that start with a partially wet canopy. When taking it too long, intermittent rain events are joined into a single event. The 2-h length of the dry period was estimated subjectively as a realistic optimum in our rain climate and is in fair agreement with other studies. The influence of the length of the dry period was analysed by a comparison with periods longer than 2 h.

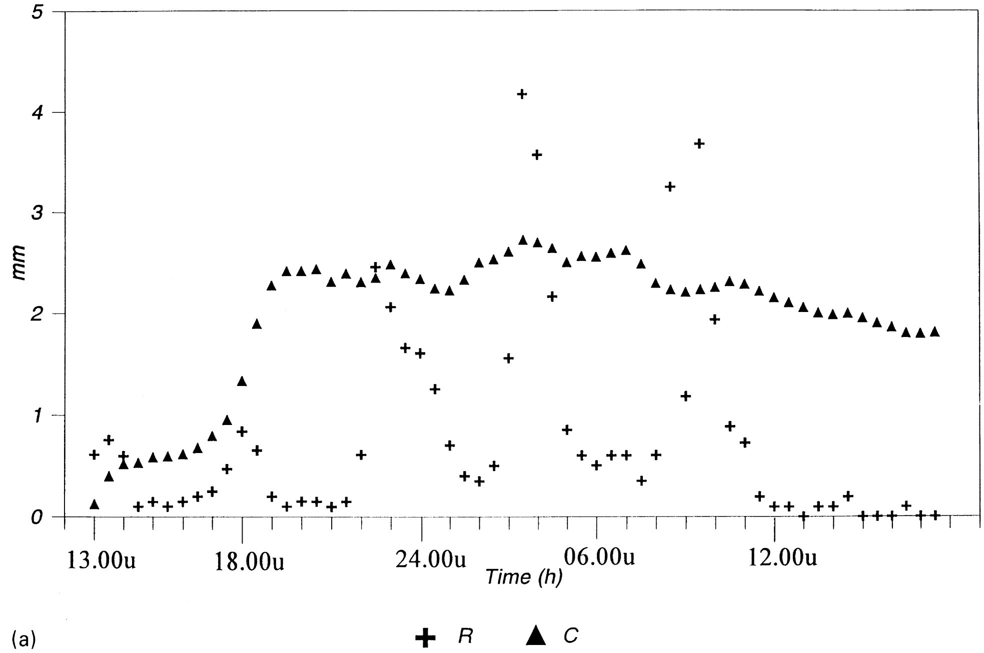
Validation data of water storage and evaporation were selected more stringently. Firstly, a shorter period (June–October) was used when all validation instruments operated adequately. Secondly, in order to keep the assumptions of Eq. (3) realistic, the dry period criterion was shortened to 30 min and only events were selected that initially had less than 10% of the maximum water storage during that event. As a result, only 14 events remained for analysis. All events consist of continuous rain, defined as $R > 0.1$ mm h^{-1} over each 30 min.

4. Results

4.1. Water storage

As an example, the change with time of water storage, rain intensity, specific moisture deficit and evaporation are shown in Fig. 1 during a long-lasting rain event. Water storage increases with precipitation (the integral of rain intensity) until the canopy becomes saturated. During saturation, the water storage increases slightly with rain intensity (at 3.00 h) and decreases slightly near the end of the event, when the light rain is insufficient to compensate for the evaporative loss. This example shows that water storage at the end of an event (C_e) may fall below its maximum value during that event.

Fig. 2 shows water storage at the end of all 14 events versus precipitation. Water storage is measured



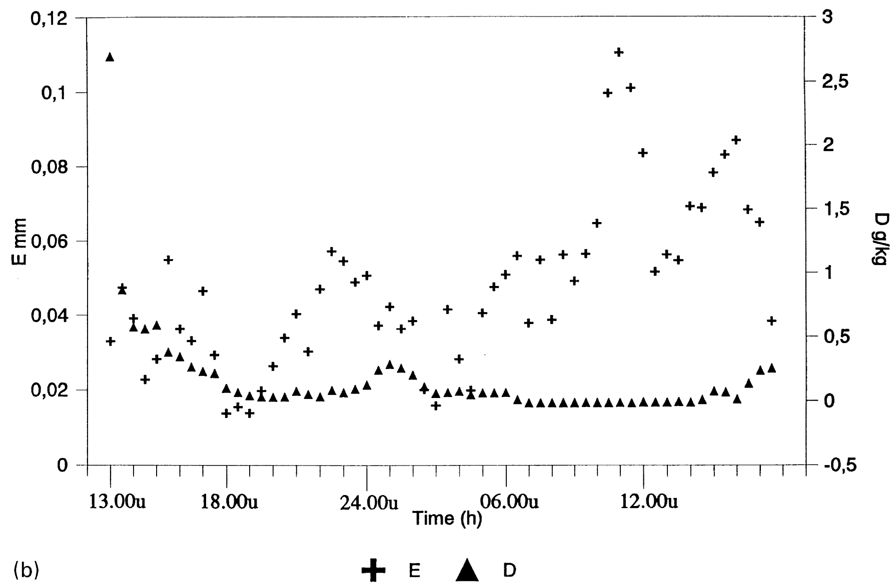


Fig. 1. (a) Rainfall (R; in mm per 30 min) and water storage (C; in mm) versus time, during and immediately after the rain event lasting from 13.00 h on 3 June 1989 to 12.30 h the next day, in Douglas fir forest. (b) Evaporation (E; in mm per 30 min) and humidity deficit (D; in g kg^{-1}) above forest during the same rain event as in (a). After midnight, the humidity sensor became gradually wetted by splashing rain drops. Note the low evaporation rate at the start and the high evaporation rate around the end of the rain event.

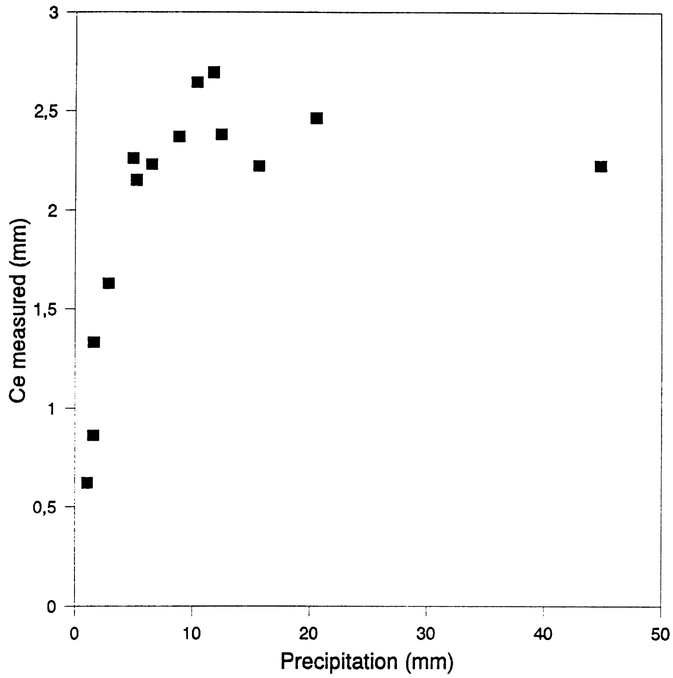


Fig. 2. Water storage at the end of a rain event versus precipitation. From this figure, it is estimated that $P_s \approx 8$ mm, an order of magnitude larger than calculated from the waterbox concept (Eq. 11). The largest rain event ($P = 46$ mm) showes only a moderate water storage at the end. This event was shown in more detail in Fig. 1. The moderate storage is explained by increasing evaporation and decreasing rainfall rate towards the end of the event.

with the microwave instrumentation and increases to $C_e = 2.4 \pm 0.2$ mm for rain events with $P > 4$ mm.

4.2. Evaporation

Evaporation falls to low values during rain and increases again near the end of the event (Fig. 1b). The humidity deficit decreases quickly, from 2–3 g kg^{-1} at the onset of rain to values that are an order of magnitude smaller during continuous rain. The low humidity deficit and low irradiation due to cloudiness may explain the low evaporation rate during rain. Note that the low evaporation rate at the start of rain events contradicts the theory that the low humidity deficit results from high evaporation of the rain-wetted earth surface (Morton, 1984). Instead, it seems that the humidity deficit decreased because of evaporating raindrops (Klaassen et al., 1996) and this process depressed the surface evaporation rate. Although high evaporation rates were not observed during rainfall, evaporation frequently exceeded the limited available energy, in agreement with Stewart (1977). Instead, high evaporation rates were frequently observed in the drying phase just after an event, when available energy and humidity deficit increased, in agreement with Singh and Szeicz (1979).

After 6.00 h, the observed humidity deficit in Fig. 1b has vanished as the ‘dry’ thermocouple became wetted by rain splash. Towards the end of the event, the thermocouple dried slowly, but might still underestimate the humidity deficit. The evaporation rate appeared to increase towards the end of this event. It is suggested that the increase of evaporation towards the end of the event results from advection of drier air and an insufficient rain rate to completely moisten this advecting air.

Evaporation during rain averaged $E = 0.077$ mm h^{-1} or 55 W m^{-2}. Total evaporation during rain is poorly related to precipitation ($c(Et,P) = 0.66$ for all events with $P > 4$ mm; see Fig. 3). Modelled

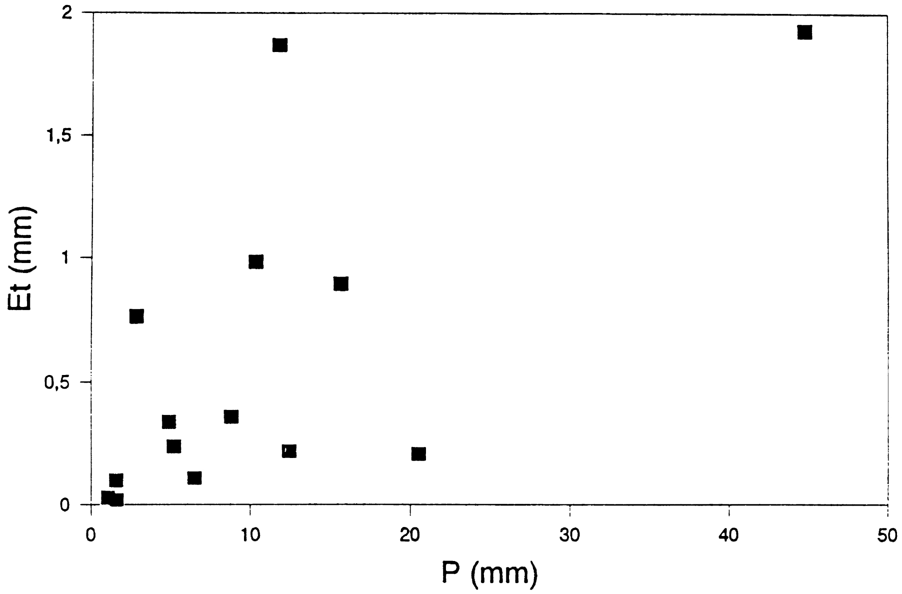


Fig. 3. Evaporation during rain versus precipitation for 14 events with detailed measurements. On average, evaporation during rain is only 4.6% of precipitation.

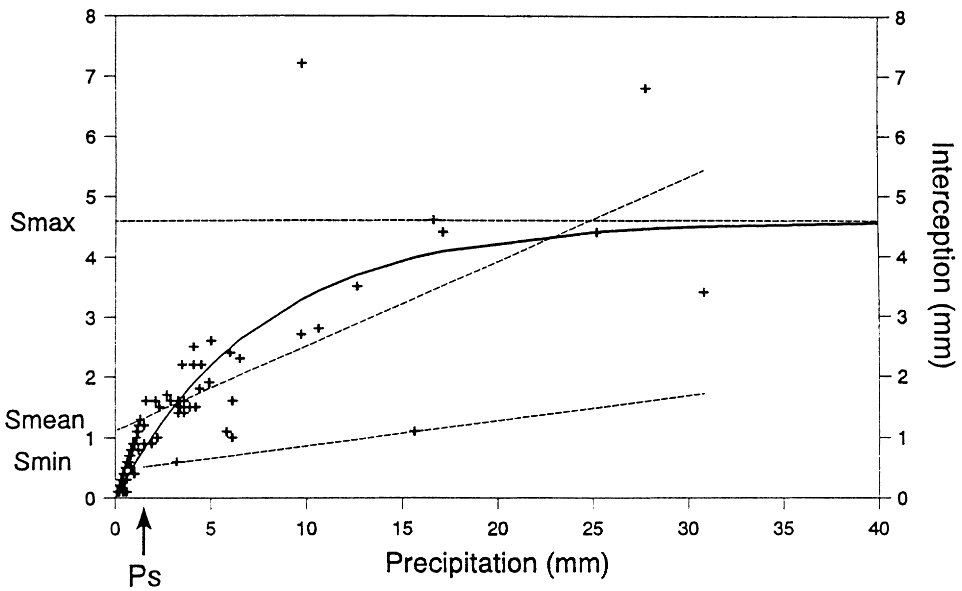


Fig. 4. Interception versus precipitation for all rain events between May and December 1989. P_s is the amount of precipitation needed to saturate the canopy according to the waterbox concept, S_{min} is the water storage capacity as determined from a fit on observations of minimum interception and $P > P_s$, S_{mean} is determined from a linear fit on $P > P_s$, and S_{max} is the upper limit as determined from an exponential fit to all data.

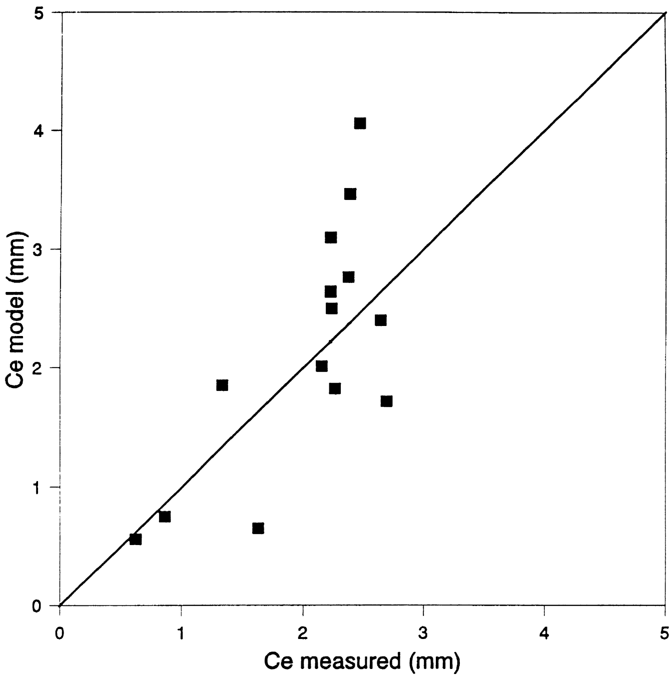


Fig. 5. Simulated water storage at the end of rain events versus observed storage using the maximum method. Note that the minimum and mean methods underestimate water storage by constant values of 0.4 and 1.2 mm, respectively.

transpiration averaged 12 W m^{-2} and was found mainly during the first hour of rainfall on summer days, when the canopy was still unsaturated.

4.3. Model results

Water storage capacity has been determined from the measurements of rainfall inside and outside the canopy (Fig. 4), with interception accounting for the difference between the rainfall observations (Eq. 3).

The minimum water storage capacity S_{min} was calculated from only two events (with $P = 3$ and 16 mm), resulting in $S_{min} = 0.4$ mm. Including the events with $P = 6$ and 31 mm would give a similar result. The mean water storage capacity S_{mean} appeared to depend slightly on the choice of the amount of precipitation needed to saturate the canopy (P_s) (see Section 5.3). P_s is commonly estimated rather subjectively from the curve in the I versus P graph (Fig. 4; see Leyton et al., 1967). An objective procedure was preferred in this study, with a fit through the origin for $P < P_s$ and varying P_s until a continuous fit is found at P_s. This iteration on Eqs. (4) and (6) results in $P_s = 1.4$ mm, $p = 0.1$ and $S_{mean} = 1.2$ mm, in agreement with common estimates. From the exponential fit $I = 4.6\{1 - \exp(-0.13P)\}$, the maximum water storage capacity is derived as $S_{max} = 4.6$ mm.

According to the waterbox concept, water storage at the end of an event equals water storage capacity for $P > P_s$. As compared to the measured storage $C_e = 2.4$ mm, the waterbox concept methods strongly underestimate water storage: $S_{min} = 0.4$ mm and $S_{mean} = 1.2$ mm. The maximum water storage capacity ($S_{max} = 4.6$ mm) overestimates the observed water storage, as complete saturation is never reached according to the maximum method. Following this method, water storage is calculated from Eq. (13). As Eq. (13) results in a variable C_e for different rain events, the average values should not be compared (as was done for S_{min} and S_{max}), but instead the differences between the observations should be analysed. Water storage, calculated using Eq. (13), compares favourably on average with the measurements, although the scatter is relatively large: C_e(model) $=$ C_e(observed) $- 0.1 \pm 0.7$ mm (Fig. 5).

Table 1
Directly observed water storage capacities

S (mm)	Species	Method	Reference
0.2–0.6	Eucalyptus	Tree weighing + artificial rain	Aston (1979)
0.35	Eucalyptus	Weighing lysimeter	Dunin et al. (1988)
0.39	Eucalyptus	Laboratorium water soaking	Crockford and Richardson (1990)
1.0	Monterey pine	Tree weighing + artificial rain	Aston (1979)
2.5	Sitka spruce	Branch weighing	Hancock and Crowther (1979)
2.4	Sitka spruce	Gamma ray attenuation	Olszyczka and Crowther (1981)
2–8	Mixed tropical	Water soaking	Herwitz (1985)
2–3	Sitka spruce	Gamma ray attenuation	Calder and Wright (1986)
2.8 (2.1)	Sitka spruce	Water soaking (and shaking)	Hutchings et al. (1988)
1.1	Picea	Tree weighing + artificial rain	Teklehaimanot and Jarvis (1991a)
2.4	Douglas	Microwave transmission	This study

Only the mean method results in an indirect estimate of evaporation. Using Eq. (6) results in $E = R{\cdot}\delta I/\delta P = 0.14R = 0.23\ \mathrm{mm\ h^{-1}}$. So, the mean method overestimates evaporation by a factor of three as compared to the direct measurement.

5. Discussion

As the results of the established methods (S_{min} and S_{mean}) deviated strongly from the measurements, the quality of the measurements was checked. Possible systematic errors in the methods and a comparison with previous studies, together with the implications of these results for assessing the performance of models, are discussed below.

5.1. Water storage

The accuracy of the microwave transmission method has already been discussed by Calder (1991) and Bouten and Bosveld (1991). An error of 0.3 mm is expected in the calibration of the instrument. This is much smaller than the observed difference using the indirect methods to determine water storage.

Direct observations of water storage capacity show an order of magnitude variation (Table 1). All methods show $S < 1$ mm for Eucalyptus and $2 < S < 3$ mm for Sitka spruce, despite the large variation in measurement methods. This suggests that the differences in the direct methods are related to species differences, rather than measurement method differences. For instance, the water storage capacity of Eucalyptus is small due to the low leaf area index, smooth bark and hydrophobic leaves (Crockford and Richardson, 1990). The present method using microwave transmission appears to be in good agreement with previous direct measurements on a similar tree species, the Sitka spruce (Table 1). So, the discrepancy between our direct and indirect estimates of water storage capacity is unlikely to be the result of a systematic error in the direct measurement.

Also, our results using indirect methods agree with previous studies. A review by Zinke (1967) results in $S_{mean} = 1.3$ mm, and a review by Shuttleworth (1989) results in $S_{min} = 1.2$ mm. These results were averaged over a wide range of forest tree species. So, the present results of water storage as calculated by the minimum and mean methods are not coincidental and, given the difference with direct observations, seem susceptible to systematic errors.

5.2. Evaporation

A direct measurement of the evaporation rate is problematic during rain, due to the risk of wet sensors. Special care has therefore been taken to select useful data. About half of the time during rain, only one of the two measurement techniques (eddy correlation and profile) could be used. When both methods were used, a two-fold stochastic variation in the 30-min averages of the methods was usually found. Using averages over longer periods, however, the profile and eddy correlation methods agreed within 15%. The accuracy of our average ($E = 55\ \mathrm{W\ m^{-2}}$, or $0.077\ \mathrm{mm\ h^{-1}}$) is estimated to be of similar

Table 2
Evaporation rate according to the mean method

Species	Remark	E (mm h^{-1})	Reference
Mixed evergreen	Night	0.37	Pearce et al. (1980)
Mixed beech	Summer	0.46	Pearce and Rowe (1981)
	Winter	0.28	Pearce and Rowe (1981)
Savanna bush		0.7	De Villiers (1982)
Evergreen beech	Summer	0.53	Rowe (1983)
	Winter	0.39	Rowe (1983)
Oak	Summer	0.32	Dolman (1987)
	Winter	0.11	Dolman (1987)
Acacia	1977	0.61	Bruijnzeel and Wiersum (1987)
	1978	1.13	Bruijnzeel and Wiersum (1987)
Mixed tropical		0.34	Hutjes et al. (1990)
Picea	Close spacing	0.17	Teklehaimanot and Jarvis (1991b)
Maritime pine	Summer	0.18	Loustau et al. (1992)
	Winter	0.11	Loustau et al. (1992)
Maritime pine	Summer	0.09	Lankreijer et al. (1993)
Oak	1988	0.16	Lankreijer et al. (1993)
	1989	0.24	Lankreijer et al. (1993)
Shrubs	Semi-arid	2.95	Navar and Bryan (1994)
Douglas		0.23	This study

magnitude, say 20%. Another possible systematic error in the measurement is the correction for transpiration. However, the correction for transpiration (12 W m^{-2}) is too small to explain the difference with the mean method. Another possible source of error may be the different data selection for the direct and indirect methods. The indirect 'mean' method was extended to December and the direct measurements ended in October. However, the evaporation rate was found to decrease in the autumn, so this limitation could even result in an overestimation of evaporation during the time of rainfall measurements and thus it cannot explain the difference between the mean method and measurements. The seasonal variation of evaporation found in this study is in agreement with indirect estimates (Table 2).

A further comparison of the results on measured evaporation is made with previous studies. Given the difficulties in measuring evaporation during rain, only a few published studies can be found to compare with our results.

Stewart (1977) observed $E = 129$ W m^{-2}, or 0.19 mm h^{-1}, using Bowen Ratio measurements. Gash (1979) found a very similar evaporation rate for the same forest using the Penman–Monteith equation with zero surface resistance. These values are more than a factor of two higher than those found in the present study. This difference is unlikely to be caused by differences in rain climate, as these are small between The Netherlands and England. Also, the correction for transpiration in the present study is too small to explain the difference between the results of Stewart (1977) and Gash (1979) on the one hand, and the present study on the other. The measurements by Stewart (1977) were limited to the daytime and an available energy of $A > 20$ W m^{-2}. In the daytime, higher average values of evaporation rate may arise, as energy for evaporation can be advected from upwind dry areas receiving solar radiation (Stewart, personal communication). A check indeed showed that, for $A > 20$ W m^{-2}, the sum of evaporation and transpiration averaged 108 W m^{-2} in the present dataset, which is twice the average value for the complete dataset and in good agreement with the result of Stewart (1977) under the same restriction. The measurements by Gash were analysed using the aerodynamic roughness length for momentum transport. A correction for the roughness length for water vapour transport (Lankreijer et al., 1993) would make the results consistent with those of Stewart (1977) and the present study.

Dunin et al. (1988), using microlysimetry, found an

Table 3
Sensitivity of water storage to the minimum length of the dry period between rain events

T_{dry} (h)	S_{min} (mm)	S_{mean} (mm)	S_{max} (mm)
2	0.4	1.2	4.6
4	0.5	1.3	4.6
12	1.1	0.8	6.1

average value of $E = 0.1$ mm h^{-1}, only slightly above our result ($E = 0.077$ mm h^{-1}), although extreme evaporation rates up to 0.8 mm h^{-1} were found. Given the warmer climate in eastern Australia, the average result of Dunin et al. (1988) agrees well with our direct observation of evaporation. So, the present results of measured evaporation are in good agreement with previous results.

The indirect estimation of evaporation using the mean method is sensitive to climate (Table 2). Summer values exceed winter values. The highest values are found for semi-arid vegetation, followed by tropical forest, closed temperate forest and open forest (Maritime pine). The sensitivity of evaporation rate to forest density has been discussed by Teklehaimanot et al. (1991) and Gash et al. (1995). The result of the present study using the mean method is consistent with previous studies using the same method on a closed forest in a temperate climate. The good agreement with previous studies shows that our results using the mean method are not accidental and are not susceptible to systematic errors. Note that evaporation could not be calculated from the minimum or maximum method, so consideration of evaporation is restricted to the mean method.

5.3. Errors in the models

The models were applied to a dataset in which rain events were separated by dry periods (T_{dry}) of at least 2 h. Table 3 shows that the results are almost identical for $T_{dry} = 4$ h. Using $T_{dry} = 12$ h results in a strong decrease in the number of rain events, as many events are joined to a few large intermittent rain events. The small number of rain events with $T_{dry} = 12$ h results in more stochastic scatter and a less accurate determination of water storage capacity. It is concluded that the methods are only marginally dependent on the selected length of the dry period, and the underestimation of the indirect methods cannot be explained by inadequate data selection.

The methods based on the waterbox concept assume $\delta C/\delta P = 0$ for $P > P_s$. However, measured water storage (Fig. 2) appears to increase until $P =$ 8 mm, almost an order of magnitude greater than used in the fitting procedure ($P_s = 1.4$ mm). So, the waterbox methods have been re-analysed using $P_s = 8$ mm.

Least square fitting for $P > 8$ mm results in $S_{mean} =$ 3.3 ± 1.9 mm, in good agreement with observations, although the accuracy is strongly diminished by increasing P_s. By increasing P_s to 8 mm, the number of data is marginal to obtain relevant data for S_{min}: by taking the data at $P = 10$ and 31 mm and suggesting that the measurement at 16 mm was below a dripping point, $S_{min} = 2.3$ mm is obtained. By using only the data with $P = 16$ and 31 mm, a negative S_{min} would result.

The good result of the maximum method, C_e(model) $= C_e$(observed) $- 0.1 \pm 0.7$ mm, can now be explained by the low evaporation rate, $E =$ 0.077 mm h^{-1}, so errors from the assumption in Eqs. (12) and (13) stay small. However, the constant $S_{max} =$ 4.6 mm is a factor of two above the observed water storage ($C_e = 2.4$ mm), suggesting that S_{max}, as defined in Section 2.2.3, is an empirical parameter with restricted physical meaning.

Only the mean method is useful in calculating the evaporation rate. By increasing the precipitation needed for saturation to $P_s = 8$ mm, the mean method results in $E = \alpha R = 0.08 \pm 0.13$ mm h^{-1}, in good agreement with the direct observations ($E =$ 0.077 mm h^{-1}), although the agreement might be accidental given the large confidence interval. Using least square fitting, evaporation is given by Eq. (5), so errors in the mean method may result from the assumption $\delta C/\delta P = 0$ for $P > P_s$, as well as from the assumption that the correlation coefficient $c(Et,P) = 1$ for $P > P_s$. Fig. 2 shows that the assumption $\delta C/\delta P = 0$ is better fulfilled for $P_s > 8$ mm, but Fig. 3 shows that errors may still arise due to the restricted correlation between precipitation and evaporation.

5.4. Implications

The discussion so far indicates that water storage is the dominant proces in interception of rainfall on dense vegetation and that evaporation during rain is of secondary importance. Note that dominance of water storage is determined for continuous rain, i.e. evaporation in the dry periods between successive rain events should not be taken into account. Note further that this conclusion does not mean that evaporation is, in every situation, smaller than storage. In our situation, with $S = 2.4$ mm and $E = 0.077$ mm h^{-1}, evaporation would exceed storage after 31 h of continuous rain.

It will be analysed whether the implications of storage as the dominant process of rainfall interception are acceptable. The following analysis is partly speculative, as only limited data are available to check the arguments.

The minimum and mean methods have been used extensively with satisfying results. A change by a factor of two or more in a basic parameter (S) of these methods might conflict with previous results. When only water storage capacity would be increased, the modelling of interception would deteriorate. In order to yield realistic results, it is recommended to decrease the evaporation rate during rain as well, for instance by using an appropriate roughness length for water vapour transport (Lankreijer et al., 1993). A decrease of evaporation rate does not conflict with the studies of Stewart (1977) and Gash (1979) (see Section 5.2), as the observations by Stewart (1977) were restricted to the daytime.

The present results on water storage and evaporation during rain indicate that high interception values should be found for species with high water storage capacity instead of species with high aerodynamic conductance. Indeed, the few studies on dense, low vegetation show high interception values (Leyton et al., 1967; De Villiers, 1982; Navar and Bryan, 1994; Leuning et al., 1994).

Deforestation often results in increased river discharge (Bosch and Hewlett, 1982). This is often attributed to the high interception loss of forest. Interception loss is defined as supplementary water use due to evaporation of intercepted precipitation. The modest evaporation rate during rain, found in this study, implies interception loss to be modest during rain. However, a large interception loss of aerodynamical rough vegetation can still be explained by a high evaporation rate from the wet canopy directly after rain, due to increases of available energy and humidity deficit (Singh and Szeicz, 1979). The smaller interception loss of low vegetation may be explained by the smaller evaporation rate after rain, resulting in a longer drying time and a shorter time for transpiration of aerodynamically smooth vegetation. By contrast, at wind-exposed forest edges, a higher water use is explained by a shorter drying time and longer time available for transpiration (Klaassen et al., 1996).

Studies of rainfall interception on a larger scale indicate an overestimation of water storage by vegetation (Dolman and Gregory, 1992), contrary to the present findings. This discrepancy is explained by spatial variability of rainfall and canopy water storage (Eltahir and Bras, 1993). At the moment, subgrid parameterization of rainfall variability still requires some empirism. So, increasing water storage capacity of vegetation in large-scale models is feasible when accompanied by an appropriate estimate of subgrid variability. Radar satellites may provide the information to estimate subgrid variability in water storage after rain (Klaassen et al., 1997).

6. Conclusions

This study sheds new light on the division of interception into water storage and evaporation during rain. The 14 events which could be studied in detail resulted in a summed water storage at the end of the event of 28 mm and a summed evaporation during rain of only 8 mm. It is concluded that water storage is the dominant process in interception of dense forest and evaporation during continuous rain is of minor importance. This conclusion is based on direct observations of water storage and evaporation. The observations appear to be in good agreement with previous direct observations. So, it is concluded that the measurements are basically correct. Studies in less dense forest and other climates may yield another division between water storage and evaporation.

The measurements have been used to validate three methods that discriminate between the parameters water storage and evaporation during rain that make up interception, and are based on rainfall observations. Two methods (‘minimum’ and ‘mean’) have been in general use for decades. These methods appear to disagree with the observations. The mean method resulted in 13 mm storage and 23 mm evaporation, suggesting that evaporation is the dominant process. The minimum method performed even worse because of stochastic errors. By comparison with previous studies, it was shown that our results with these methods are not accidental. It is concluded that these methods are affected by a systematic error. The error is explained to result from the neglect of drainage from a partly saturated canopy.

The third, 'maximum' method accounts for drainage by assuming gradual saturation of a larger water storage capacity. This method resulted in a realistic discrimination between water storage and evaporation during rain. The good estimate of water storage by the maximum method can be explained by the limited evaporation during rain.

When water storage is increased in a simulation model, it will often be necessary to decrease the evaporation rate during rain as well to obtain a realistic estimate of total interception. A previous study by Lankreijer et al. (1993) showed that the evaporation rate can be decreased with an appropriate resistance for water vapour transport.

The relatively good discrimination by the maximum method between storage and evaporation during rain does not necessarily mean that this method is the best to simulate interception. Recent research into Soil–Vegetation–Atmospheric Transfer has resulted in many models. Many of these models allow for drainage of a partly saturated canopy. It is recommended to compare these models (e.g., Pitman et al., 1993). The present study emphasizes the need to compare not only total interception, but also the discrimination between storage and evaporation. Therefore, it is recommended to build high quality datasets with direct measurements of water storage and evaporation during rain. Given the indication that interception is significant for low vegetation as well, these data should preferably be gathered over all main vegetation types.

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